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Analysis of Liquid Cooling in Microchannels Using Computational Fluid Dynamics (CFD)

Chitra Boobalan, Sudha Ganesh and Parthiban Rangaswamy

Abstract

Liquid cooling is an extremely successful process to remove excess heat generated, with the usual procedure of heat transfer using coolant in desktop PCs. In this regard, heat transfer with minimal size equipment can be achieved by the addition of nanosized solid particles to the base fluid. The hybrid nanofluid is synthesized by dispersing the synthesized mono nanofluid in a volume fraction of 0.2 iron oxide with 0.8 fractions of graphene nanofluid to form a graphene/iron oxide combination. These nanoparticles increase the heat transfer coefficient as they have high thermal conductivity when compared to conventional heat transfer fluids like water or ethylene glycol. Stability is increased and sedimentation is reduced because of the large surface area of a nanoparticle. FLUENT, the most widely used computational fluid dynamics (CFD) software package, based on the finite volume method, and is used to run the thermal simulations for estimating the base temperature of the heat sink. The scope of this chapter is to find the base temperature of the heat sink using simulations. The experimentally measured base temperature is 310.01 K and in the simulation, it is 310.81 K for the flow rate of 0.75LPM. All the simulated surface temperatures are compared with experimentally determined temperatures for simulation validation.

Keywords: microchannel, nanocoolant, base temperature, CFD

1. Introduction

Liquid cooling in microchannels is a highly successful method of removing excess heat from the circuits, with water being the most common heat transfer fluid on the desktop. The important advantage of using water cooling over air cooling is due to enhanced thermal properties of water (higher thermal conductivity and heat capacity property).

The noteworthy development of power densities in the Central Processing Unit (CPU) chips and also the reduction of their surface area contribute to the production of high heat flux. Computers and the processor's thermal management and its operation without overheating are a difficult task nowadays. The increase of transistors used in the circuit has reached up to 580 million. Microelectronics devices are safe on their operating temperature for the range of 70–80 °C and the reliability is decreased 5% for every degree rise in temperature. One sensible manner is to

use liquid fluid to gain the generated heat by convective means and deliver it to the external surroundings. Also, convective systems have the potential to be designed for various configurations. As proved in [1], bulk heat transfer is more significant than the thermal properties for most applications because bulk transport is the main reason for heating or cooling. This micron-sized particle, when used in low volume fractions prevents particles clogging and also reduces the pressure drop.

PC coolers are helpful for this reason using appropriate working liquids coolant. They will greatly enhance the system's cooling performance. Heat sinks are equipped for simultaneous cooling of several chips and also processor supply circuits, graphic cards, and CPU. In employing a heat sink very low flow rates of coolants are required and thereby the noise generations are also minimal as mentioned in [2].

This liquid cooling is categorized into active and passive cooling. The principle of an active liquid cooling system for computers is the same as that used in combustion engines, with the coolant being water which is circulated by a pump. This Heat sink made of microchannels is mounted on the CPU and sometimes on the components like GPU and Northbridge and cooled typically a radiator. The radiator itself is cooled externally by employing a fan [3].

Both active liquid cooling systems and passive liquid cooling systems are used depending upon the requirements. The passive system often discards a fan or a water pump, hence the reliability of the system can be theoretically increased and or making it quieter than active systems. However, they are much less efficient in discarding the heat and thus also need to have much more coolant and thus a much bigger coolant reservoir (giving more time to the coolant to cool down).

Although liquid cooling under forced convection enables higher heat dissipation rates, air cooling is the most common technique for heat removal. The primary advantage of air cooling is its easy operability with less noise. Forced air-cooling processes may be further classified into serial and parallel flow systems. In a serial system, the air stream is passed over successive rows of modules or boards, so that each row is treated by the same air that has been preheated by the previous row. The power and airflow requirements are the key factors in serial airflow resulting in an extensive air temperature rise across the machine. Parallel airflow systems can be used to reduce the temperature rise in the cooling air. In this system, the printed circuits or modules are all equipped with a parallel air supply. In this method, each board or module is supplied with a fresh supply of cooling air [4].

2. Nano coolants in microchannels for CPU cooling

In this connection, heat transfer equipment with minimal size can be achieved by adding solid small-sized particles [5]. These particles have high thermal conductivity when compared to conventional coolants like water or ethylene glycol [6]. If the suspended particle size is in the order of microns and millimeter lot of problems like particle settlement, corrosion and more pressure drop needs to be overcome. Because of these drawbacks, milli-size or micron-size particles are not used widely. Choi and Eastman [7] tried suspending nanometer particles in a solution. The nano-sized particle and their low volume fractions prevent particles from clogging and also reduce the pressure drop. Stability is increased and sedimentation of the particle is decreased due to its increased surface area of particles [8]. The efficiency in heat removal is improved since heat transfer takes place at the particle surface. Nanosheets comprising MAXene obtained from Ti_3SiC_2 MAX phase ternary carbides can be a probable nanocoolant with very efficient thermal management. It is synthesized via shear-induced micromechanical delamination technique. It is also

known as 'rheo-controlled' nanofluid. The thermal conductivity increments are about 45% at 323 K [9]. The corrosion effect of nano coolant accompanying material loss needs to be analyzed. Coolants such as graphene nanoparticles, corrosive water, and ethylene glycol were studied and their effects on parameters like the temperature of the coolant, inlet pressure, and rpm of the pump were recorded [10]. He also confirmed that the corrosion effect was the same for both the base coolant and nanocoolant [11]. The suspended graphene nanoparticles with water as a base solvent and for various volume fractions and measured its convection coefficients for the temperature range of 30 °C to 80 °C. The heat transfer characteristics of hybrid nanofluid (HyNF) flow through the tubular heat exchanger were also studied by [12]. They examined the various parameters like thermal conductivity and heat transfer coefficient under forced convection. The experiments were performed for various nanoparticles ranging from 0.1% to 1.0% volume concentrations added in the base fluid. The results showed that the bulk heat transfer coefficient was maximum by 48.4% up to 0.7% volume concentration of HyNC.

2.1 CPU cooling with hybrid nanofluid

Labib et al. [13] employed two different base fluids of water and ethylene glycol and analyzed the effect of convective heat transfer mixing of Al_2O_3 nanoparticles. The CFD results are validated with the experimental data for Al_2O_3 /water nanofluid. The results revealed that Ethylene Glycol base fluid gives better heat transfer enhancement than that of water. The mixture of Al_2O_3 nanoparticles into CNTs/water nanofluid is a new concept of combined/hybrid nanofluid that can profitably increase convective heat transfer. Eshgarf and Afrand [14] studied the rheological behavior of COOH functionalized MWCNTs– SiO_2 /EG–water hybrid nanocoolant for application in cooling systems. They prepared the stable suspension of MWCNTs and SiO_2 nanoparticles (50:50 volume%) in a specified amount of a binary mixture of EG–water (50:50 vol.%) for the temperature range of 27.5–50 °C. From the results, it is inferred that the apparent viscosity generally increases with an increase in the solid volume fraction and decreases with increasing temperature.

Naqiuddin et al. [15] showed geometrically graded microchannel heat sink for improvements in thermal performances. They showed for a heat load of 2000 W, the average temperature of the microchannel can be reduced to 69.6°Celsius with a temperature variation of 3° Celsius. Microchannel heat sink with micro-scale ribs and grooves for chip cooling is also investigated with CFD studies [16]. The performances of various heat sink parameters like trapezoidal, rectangular, and triangular-shaped microchannel with different channel width and aspect ratio was analyzed. The rectangular microchannel showed the best performance with the aspect ratio among 8.904–11.442. The rectangular microchannel has the lowest thermal resistance, followed by the trapezoid and triangle microchannel. Wang et al. [17] designed a heat sink with micro-scale ribs and grooves for chip cooling. The cooling efficiency is more for rib-grooved microchannel than the conventional smooth rectangular microchannel through experimental and numerical approaches. The Nusselt number of rib-grooved microchannel can be 1.11–1.55 times that of a smooth microchannel. He also studied the apparent friction factor for various relative rib heights of 0.6, 0.73, and 0.85 μm .

2.2 Synthesis of nanofluid

For nanofluid synthesis, there are many key factors to be considered [18]. Stable nanofluid [19] can be formed by one and two-step methods [20]. Both one-step and two-step methods can produce nanoparticles in suspension and also agglomeration

of particles. Thus, it is required to synthesis a suspension of non-agglomerated and also well-monodispersed nanoparticles in the liquid are the key steps for the enhancement of the thermal properties of nanofluid.

To withstand the operating temperature it should high thermal stability

- i. For the homogeneity of the medium, its dispersion should be uniform
- ii. Chemical compatibility and ease of chemical manipulation.

2.2.1 Synthesis of graphene nanoparticle

Graphene oxide nanopowders are used for graphene synthesis. Quartz crucible filled with GO is kept inside the muffle furnace at 500 °C followed by the process of thermal exfoliation–reduction under air atmosphere for 4 min. The prepared graphene powder temperature is reduced to the air ambient temperature.

2.2.2 Synthesis of iron oxide nanoparticle

In 5 mL of distilled water, Iron (II) chloride tetrahydrate powder and 50 mL of isobutanol were added after which Fe^{2+} ions were formed. The aqueous organic mixture was heated to 75 °C, added dropwise for 2 hours with 0.8 M NaOH and stirred for 30 min at 500 rpm. The synthesized iron oxide nanoparticles were washed with distilled water at 75 °C and dried in an oven at 50 °C. The dried particles of iron oxide nanoparticles were calcined for 2 h at 300 °C, 100 minutes at 400 and 600 °C. The hybrid nanofluid was prepared by dispersing the synthesized mono nanofluid in a volume fraction of 0.2 iron oxide with 0.8 fractions of gra- phene nanofluid to form graphene/iron oxide combination. The prepared hybrid fluid thermal properties as given in **Table 1** are used for further simulations.

2.2.3 Experimental set up

Figure 1 illustrates the heat sink used in the experimental setup [21]. **Figure 2** depicts the channel in the fabricated heat sink fitted with Four number of K-type thermocouples Thermocouples. The fabricated dimension of the heat sink comprising microchannels is tabulated in **Table 2**. Around 1 L of hybrid coolant is prepared and it is filled in the reservoir tank. It then flows to the test loop includes a needle valve in order to facilitate the different volumetric flow rates of synthe- sized hybrid nanocoolant. Omega rotameter (+1% full-scale accuracy) was used to measure the flow rate ranging from 0.35 to 0.75 LPM. The coolant enters the inlet port of the fabricated sink and absorbs the heat generated at the bottom of the sink due to its enhanced thermal properties and exits through the outlet port. This coolant is further cooled to its inlet temperature in a radiator as depicted in the cycle. **Figure 3** represents the fabricated heat sink made of copper with inlet

Coolant - type	Density (kg/m ³)	Specific heat (J/kg/K)	Thermal conductivity (W/mK)	Viscosity (cp)
G-Feo	1049.13	3795	1.209	1.4
De-ionisedwater	995.6	4178	0.615	1.0

Table 1.
Thermo-physical properties of nano coolants at 303 K for volume fraction 0.1%.

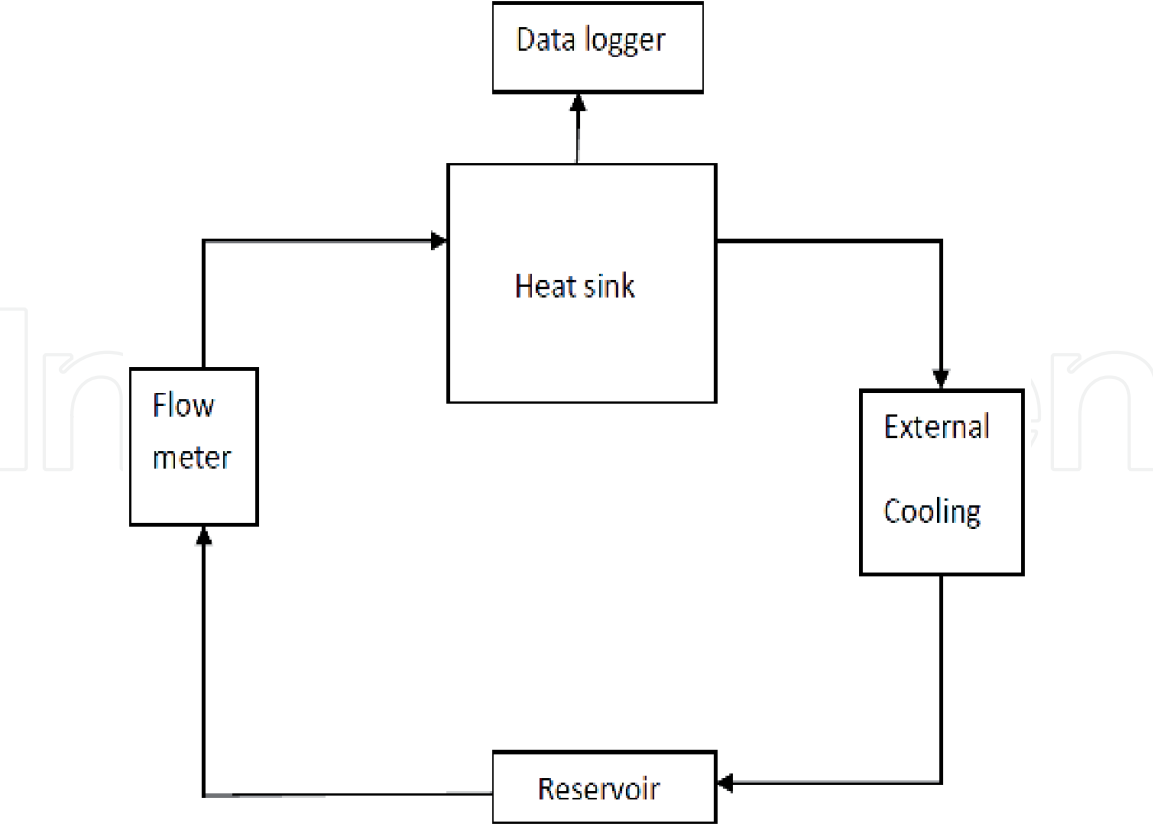


Figure 1.
Experimental flow diagram.

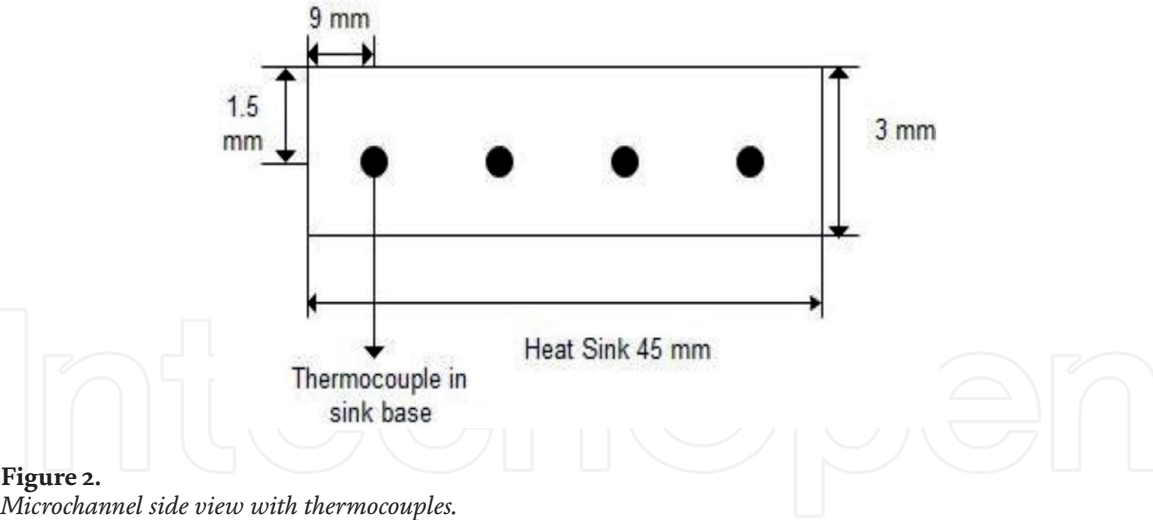


Figure 2.
Microchannel side view with thermocouples.

Various Fin parts	Dimensions (mm)
Width	55
Length	45
Height of fin	3
Width of microchannel	0.5
Heat sink base thickness	3

Table 2.
Heat sink dimension mm.

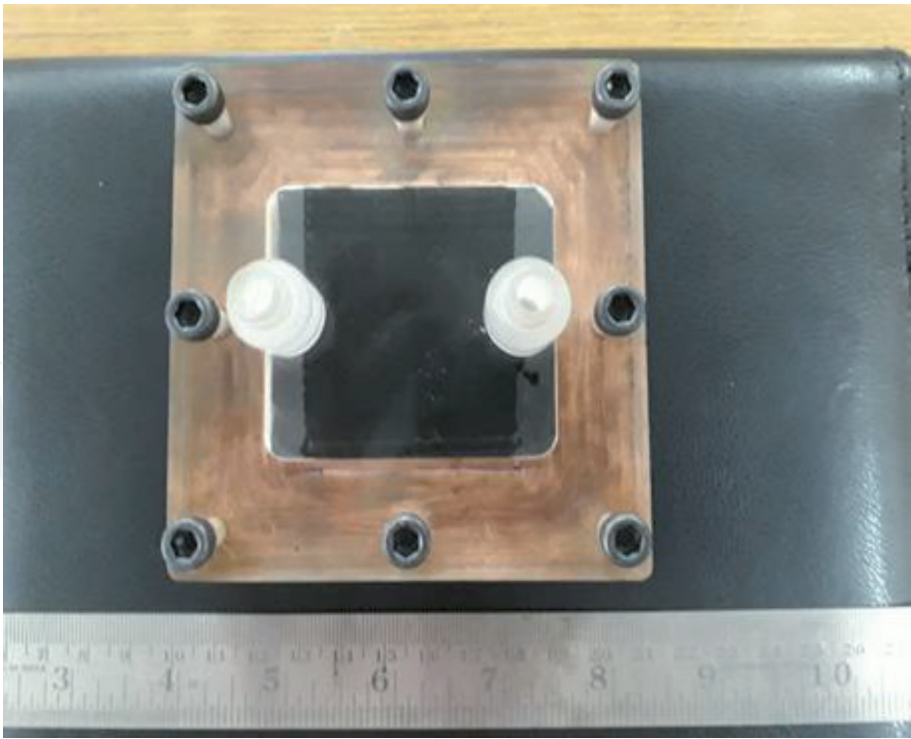


Figure 3.
Microchannel with inlet and exit ports.

and outlet ports. The average temperature of the four thermocouples indicates the experimentally measured base temperature of the heat sink.

3. Computational fluid dynamics (CFD) in microchannels

FLUENT, the most widely used Computational Fluid Dynamics (CFD) software package, based on the finite volume method, and was used to run the thermal simulations. Meshes were created, with 117353 elements, together in the fluid and solid domain. In order to simulate a fully developed flow, tubes at the inlet and outlet are selected with a length equals to 10 tube diameters.

Properties of cell mesh	
Total number of elements	117353
Elements in find domain	77408
Elements in the solid domain	39948
Orthogonal quality	
Interior fluid	0.099
Interior solid	0.1176
Minimum fluid	0.207
Minimum solid	0.164
Maximum fluid	0.990
Maximum solid	0.989

Table 3.
Generated grid values.

The fluid flow BCs used in the CFD are as follows:

- i. A constant inlet mass flow rate condition, ranging from 0.005 to 0.013 kg/s.
- ii. A constant heat flux 134.839 kW/m^2 [22] as the reference is set at the base wall of the heat sink.

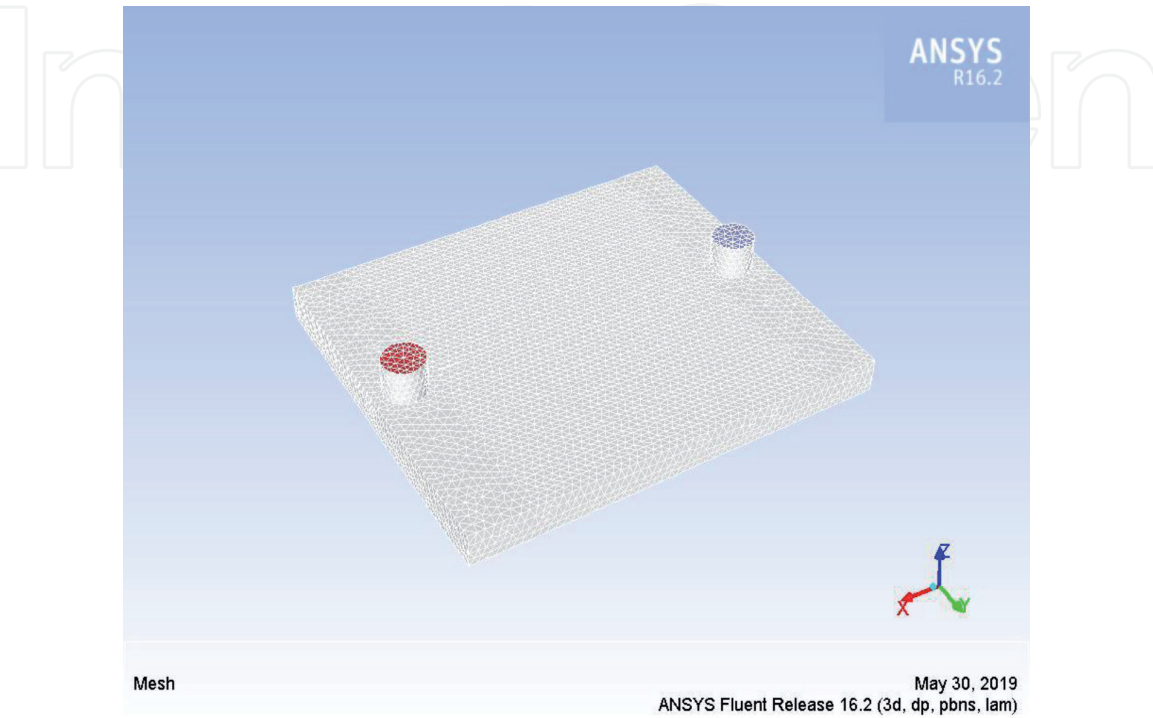


Figure 4.
Heat sink with mesh.

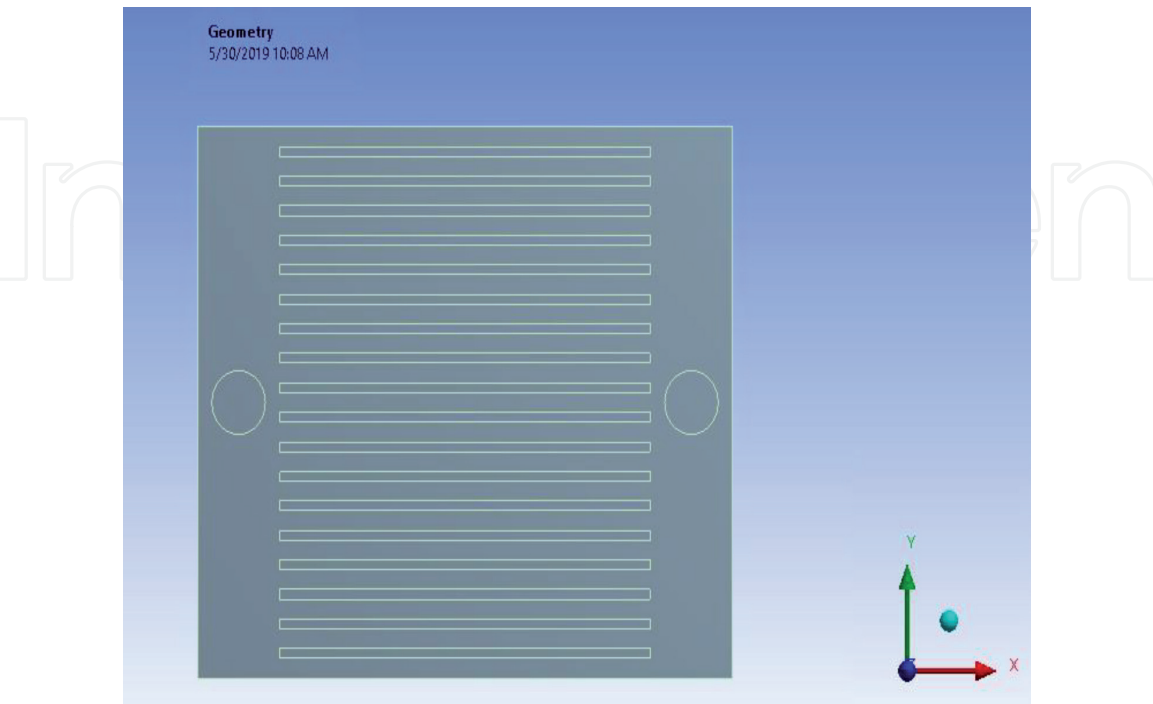


Figure 5.
Top view of heat sink geometry.

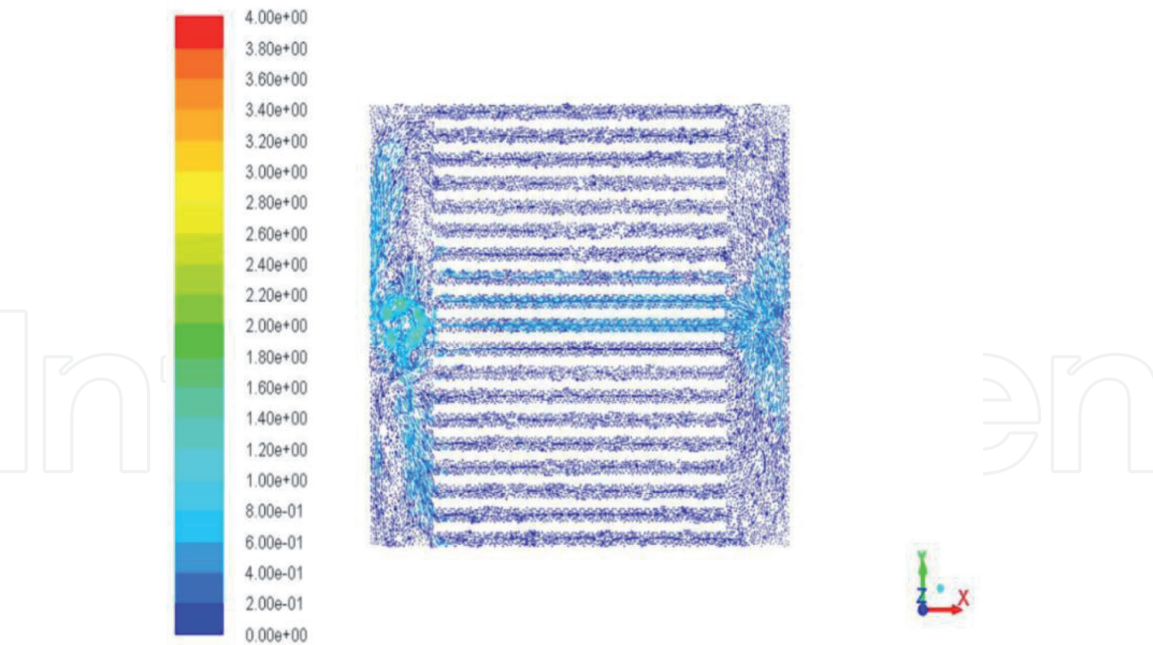


Figure 6.
Top view of microchannel showing velocity vector.

As a basic assumption, a fully developed flow (pressure outlet) is imposed. At all walls, a zero velocity (No-slip condition) boundary condition is applied and simulations are performed until the steady-state value of T_{base} is attained. The generated grid values are tabulated in **Table 3**.

Mesh with three different sizes was generated for the grid independency test. With maximum mesh size of 2 mm (mesh-1), 1 mm (mesh-2) and 0.75 mm (mesh-3) respectively. The change in Average temperature values between (mesh-2) and (mesh-3) is only about 0.4%. So, mesh-2 with a size of 1 mm is used in further simulations. The typical microchannel with final meshing is shown in **Figure 4**. The top view of the heat sink without meshing is shown in **Figure 5**.

Simulations are performed for laminar flow in the channel path of the fabricated heat sink and examined for various conditions. **Figure 6** indicates the top view of the microchannel with the velocity vector showing the fluid flow directions. The direction of the velocity vector indicates the flow of the hybrid coolant from the inlet to the outlet port through the microchannels.

4. Various contours of graphene - iron oxide

The temperature contours of graphene - iron oxide coolant are shown in **Figures 7–9** for 0.05 volume %, 0.075 volume %, and 0.1 volume % respectively. These contours represent the temperature distribution all along the length of the channel from inlet to exit port in the X direction. From these contours, it is implicit that the coolant temperature increases as it flows along the length of the channel. From **Figure 9**, it is inferred that more heat is absorbed for 0.1 vol % graphene - iron oxide coolant and the base plate temperature of the heat sink was 310.81 K for 0.1 volume fraction of coolant for the flow rate of 0.75 LPM.

4.1 Wall base temperature

The processor operating temperature (heat sink base temperature) under various flow rates for different coolant concentration is represented in **Figure 10**. It is inferred

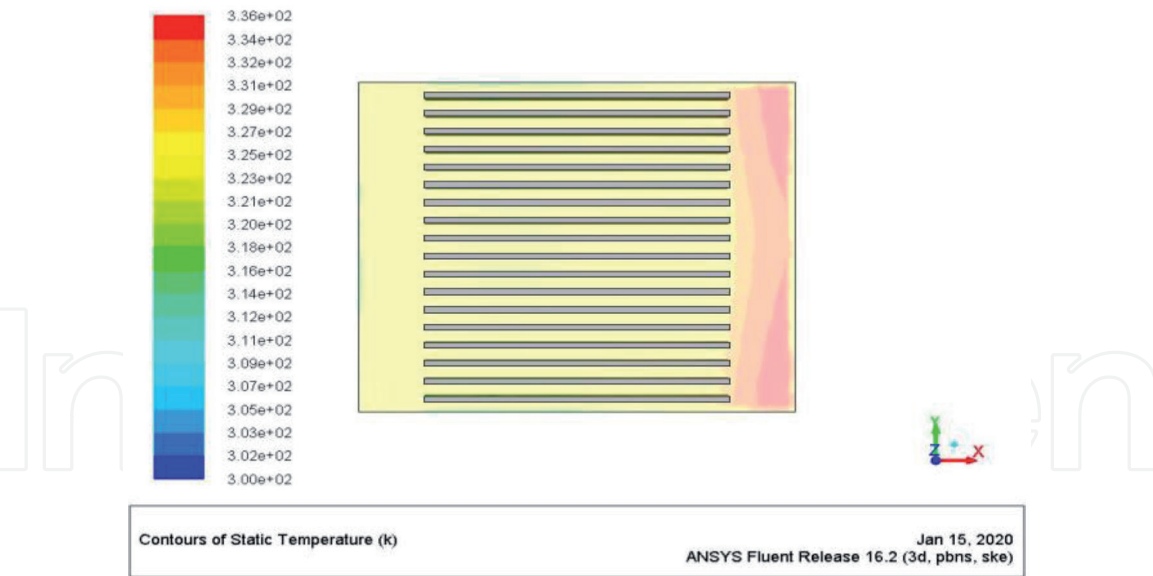


Figure 7.
Temperature contours for 0.05 volume % graphene-iron oxide.

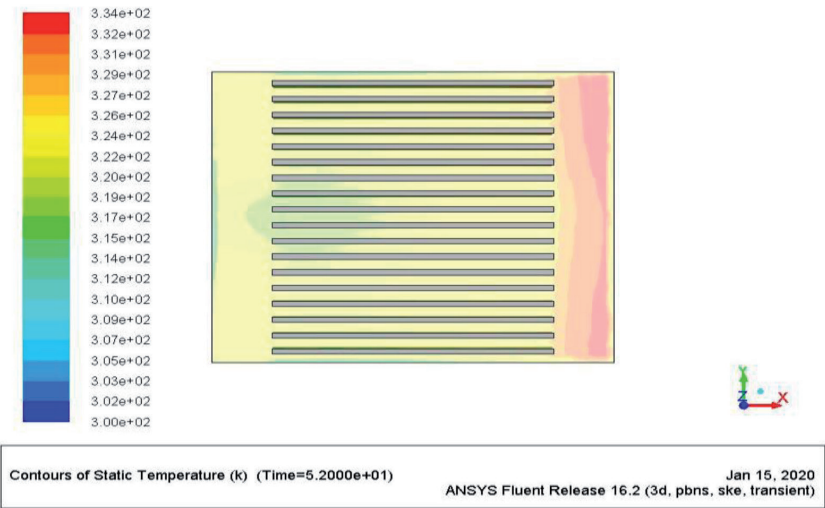


Figure 8.
Temperature contours for 0.075 volume % graphene-iron oxide.

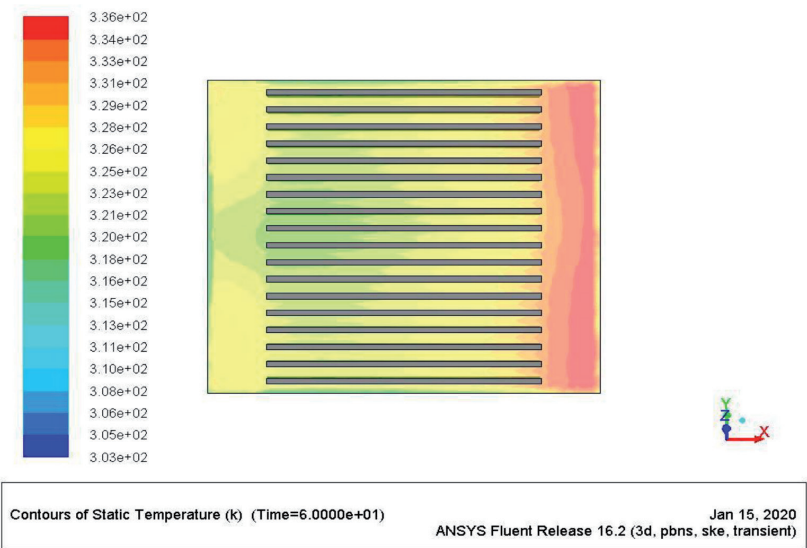


Figure 9.
Temperature contours for 0.1 volume % - graphene-iron oxide.

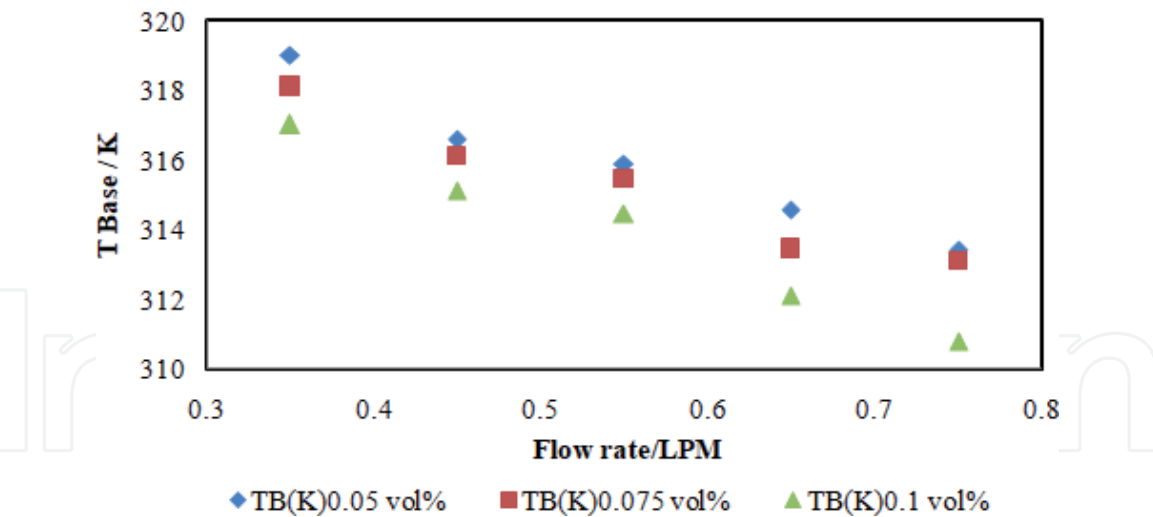


Figure 10.
Simulated base temperature versus flow rate - graphene-iron oxide.

from the graph representing the lowest temperature of 310.01 K for the concentration of 0.1 vol. % graphene-iron oxide system for 0.5 mm fin spacing while for water it is 317.05 K. These hybrid coolants because of their high thermal conductivity are capable of removing more heat when used in microchannels. The percentage reduction in base temperature when using graphene-iron oxide is 1.96%.

5. Comparison of simulated and experimental base temperatures

Figure 11 shows the comparison of simulated and experimental base temperatures for 0.1 volume % graphene – iron oxide and the correlation coefficient was found to be 0.994 which validates the model.

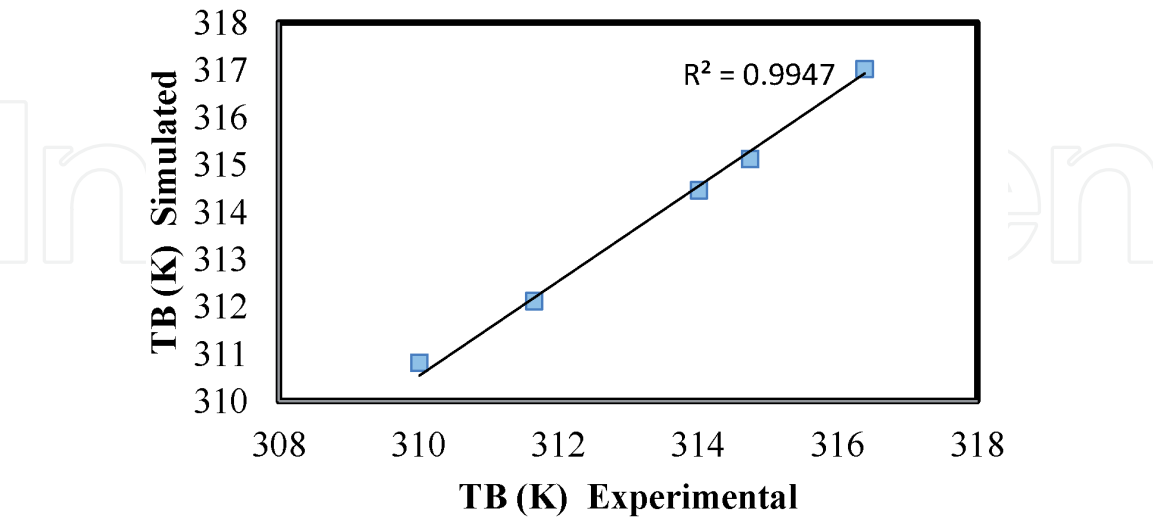


Figure 11.
Validation of experimental and simulated values of T base – 0.1 volume % graphene-iron oxide.

6. Conclusion

The present work indicates the usage of graphene as one of the components in the synthesis of hybrid nanofluids for CPU cooling by microchannel cooling

techniques. In this, graphene-iron oxide nanocoolants are used at three different volume fractions and base temperatures are measured. The experimental temperature is 310.01 K and in the simulation, it is 310.81 K for the flow rate of 0.75LPM. A comparison is made between the experimentally measured base temperatures and the simulated temperatures correlation coefficient was obtained to validate the model.

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